REPEAT-PASS INTERFEROMETRIC EXPERIMENTS WITH THE TANDEM-X CONSTELLATION FOR ACCURATE ALONG-TRACK MOTION ESTIMATION

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ABSTRACT

This contribution presents two experiments performed with the TerraSAR-X (TSX) and TanDEM-X (TDX) satellites working in the pursuit monostatic configuration. Their objective is to estimate the along-track component of the motion in the scene in repeat-pass scenarios with an accuracy better than the one given by the stripmap azimuth resolution. Such performance is possible by exploiting the angular diversity of the bidirectional (BiDi) SAR mode and the $\pi-$shifted (or staggered) TOPS.

***Index Terms*—** SAR interferometry, TOPS, dual-beam, bidirectional SAR, coregistration

1. INTRODUCTION

As is well known, differential SAR interferometry (DInSAR) allows the estimation of the motion in the scene in the line of sight (LOS) of the sensor with an accuracy proportional to the wavelength. In typical spaceborne SAR missions, this LOS is orthogonal to the along-track direction, implying that the estimated LOS motion has little or no information concerning the azimuthal motion within the scene, which corresponds approximately to the north-south component. Due to this limitation, the along-track motion is typically estimated using cross-correlation techniques, whose accuracy is limited by the azimuth resolution. In order to achieve a better accuracy it would be necessary to have either a SAR system with better azimuth resolution or a system with angular (squint) diversity. In the following, two experiments with TSX and TDX are shown, which exploit the angular diversity in different ways.

2. BIDIRECTIONAL SAR

Angular diversity has already been exploited for the two-dimensional measurement of ocean currents with single-pass platforms [1]. Recently, the dual-beam concept has been exploited with the TSX and TDX satellites working in bistatic mode [2] by using the experimental bidirectional SAR imaging mode (BiDiSAR) [3]. The BiDiSAR mode implemented in TSX and TDX exploits the phased-array antenna to generate two symmetric lobes separated by $4.4°$ (so that the grating lobe has the same magnitude as the main lobe), where this angular distance is given by the spacing between antenna elements along the azimuth dimension. Having the two beams at $\varphi_{max} = \pm 2.2°$ represents about a factor 20 improvement with respect to the angular diversity achievable within the azimuth resolution (beamwidth of $\sim 0.3°$ for TSX/TDX), hence resulting in a more accurate estimation of the along-track displacement.

In the case of repeat-pass interferometry, it is only required to have one satellite working with the monostatic BiDiSAR mode, since this mode is already giving the required angle diversity. However, considering the new pursuit monostatic phase, where the satellites are now separated by 10 seconds, one could envisage the possibility to have the first satellite looking forward and the second looking backwards, e.g., $\pm 1°$, where one should note that increasing the squint angle increases the azimuth ambiguities introduced by the grating lobe. Simultaneous squinted stripmap acquisitions with both satellites overcome the main limitation of BiDiSAR, namely, the need to increase the PRF in one platform to sample both beams without aliasing [3], hence allowing the monitoring of shallower incidence angles (the BiDi mode is usually used with very steep incidence angles to avoid large range ambiguities).

In the following, an example using BiDi acquisitions (i.e., with $\pm 2.2°$ beams) separated by 11 days is shown. The acquisitions have been performed over the Petermann glacier, Greenland, where a significant motion gradient is present. Fig. 1 shows the obtained differential interferograms after subtracting the topographic component (the DEM provided in [4] was used), where, since the BiDi angles are symmetric with respect to $0°$, the sum and the difference of the fore and aft beams yield the across-track and along-track components of the motion, respectively. In the sum interferogram, one cycle represents ~ 0.77 cm [i.e.,$\sim \lambda/(4 \cdot \cos\varphi_{max})$], while in the difference interferogram one cycle represents ~ 20 cm [i.e., $\sim \lambda/(4 \cdot \sin\varphi_{max})$]. The resulting differential interferograms need to be unwrapped, scaled and calibrated to retrieve the two-dimensional surface velocity field in meters. Note that the observed motion is in accordance with the ex-

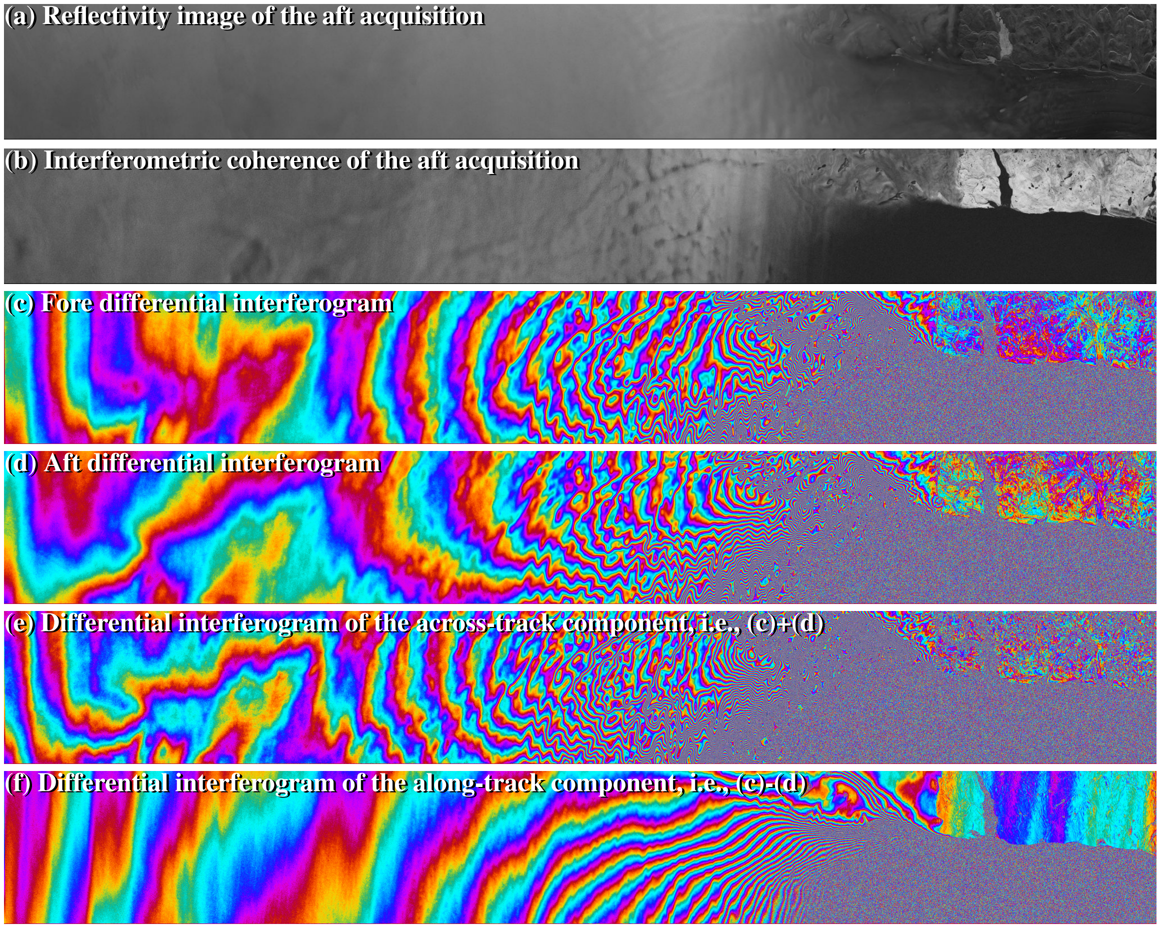

Fig. 1. BiDi interferograms with 11 days repeat pass over the Petermann glacier, Greenland. Azimuth is horizontal and near range is on top.

pected one due to the acquisition geometry with respect to the orientation of the glacier, which flows from left to right. The vertical stripes in Fig. 1(f) on the top right (over land) are probably due to ionospheric scintillations.

3. $\pi-$SHIFTED TOPS

The TOPS burst mode [5] allows a wide coverage at the expense of azimuth resolution, similar as ScanSAR. The signal is characterized by an azimuth-dependent Doppler centroid within a burst. Fig. 2 depicts the time-frequency diagram of a 1-look and a 2-look TOPS mode, where in the latter case each target is illuminated twice, i.e., under two different squint angles. The distance between these two looks can be exploited again to achieve angular diversity and obtain a better estimation of the motion in the along-track dimension [6]. The same rationale can be used with ScanSAR, with the main difference that in ScanSAR the accuracy will not be better than in the stripmap mode, as the azimuth frequency excursion is given by the stripmap bandwidth. However, in the TOPS mode the excursion depends on the antenna steering, which in the TSX/TDX case goes up to $\alpha_{max}^{steering} = \pm 0.4°$. Instead of implementing a 2-look TOPS mode, which would represent a factor two degradation of the azimuth resolution (37 m instead of 18.5 m), the present experiment consists in using the two satellites during the new pursuit monostatic phase carried out during late 2014 and early 2015, the one satellite having the same TOPS timeline as the other but shifted by half of the burst length on ground. Such mode was suggested in [7] in the frame of the Sentinel-1 mission and is defined here as the $\pi-$shifted TOPS mode. It has an angular separation given by approximately half of the maximum steering angle, as can be derived from Fig. 2. For TSX/TDX this value corresponds to $\alpha_{max}^{TOPS} \sim \pm 0.2°$. Using the 2-look TOPS, or π-shifted TOPS using two satellites, has the inherent advantage that the azimuth motion can be estimated with enough accuracy and at an almost sample-wise resolution to properly decouple the along-track and across-track components of the motion, and hence avoid phase jumps between bursts [8, 9, 10].

Fig. 4 shows the $\pi-$shifted TOPS results over the Petermann glacier. TSX and TDX acquired the TOPS data take, where TDX was separated by 10 seconds and with a TOPS timeline shifted by 50% of the burst length, as depicted in Fig. 2. Both acquisitions were acquired 11 days later, re-

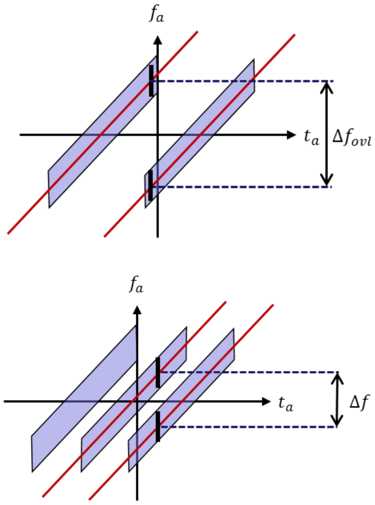

Fig. 2. Time-frequency diagram of a (top) 1-look TOPS mode and (bottom) 2-look TOPS mode implemented with two satellites. Δf is the spectral separation at the overlap area.

sulting in two independent interferograms. Figures 4(a),(b) and (c) show the reflectivity image, the coherence and a portion of the DInSAR phase of the TSX interferogram, respectively. Due to the processing with an external DEM, most of the fringes can be attributed to glacier motion. Indeed, the phase jumps between bursts are an indication of azimuthal motion [9], as this motion is projected into the line of sight with the sinus of the squint angle. A possible way to remove the phase jumps is to first estimate the azimuth shifts using conventional coherent cross-correlation and afterwards re-interpolate the slave image. However, this approach has the inconvenience that a larger multilook is required at burst edges in order to achieve the required accuracy, which in the TSX TOPS case is in the order of 1 cm [8]. Depending on the characteristics of the motion, this solution might not be feasible. Fig. 4(d) shows this intermediate result, where a coherent cross-correlation based on conventional spectral diversity has been applied, as suggested in [10]. However, a few phase jumps remain due to the spatial variability of the deformation, which cannot be tracked by this approach. Therefore, the TSX and the $\pi-$shifted TDX interferograms have been exploited to generated a differential interferogram, from which the azimuth displacement can be estimated more accurately. Fig. 4(e) shows the final result after exploiting this information, where now all the phase jumps have disappeared. It is worth remarking that the preprocessing step of applying cross-correlation might be required in most scenarios in order to ensure a residual shift within the unambiguous $\pi-$shifted band, which is about ± 1 m in the present case. If this step is not done, it might be necessary to unwrap (and calibrate) the differential phase.

As a last result, Fig. 3 shows the predicted performance for the different modes by slightly modifying the equations

Table 1. Parameters for the performance evaluation

Mode	B	Δf
Stripmap	2765 Hz	1843 Hz
BidiSAR	2000 Hz	38900 Hz
Squinted SMs	2765 Hz	17685 Hz
$\pi-$shifted TOPS	445 Hz	3200 Hz
2-look TOPS	222.5 Hz	3200 Hz

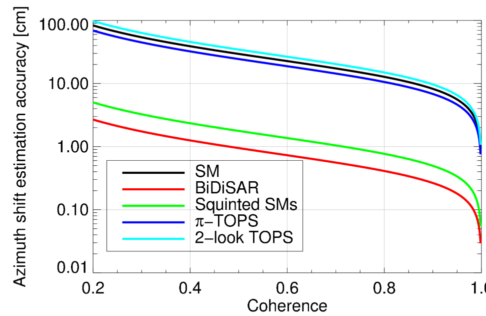

Fig. 3. Accuracy in the estimation of the azimuth shift for different modes (see Table 1). An input patch size of 100 m has been assumed.

provided in [11] in order to consider different bandwidths and spectral separations. The plot was generated assuming an input patch size of 100 m, which will result in different effective number of looks depending on the azimuth bandwidth. Table 1 summarizes the main parameters. Note that for the BiDi mode, a reduced azimuth bandwidth is set to reduce the impact of azimuth ambiguities. From Table 1 and Fig. 3 it is clear that BiDi outperforms the other modes owing to the large spectral separation, followed closely by the squinted stripmaps with $\pm 1^\circ$ squint. $\pi-$shifted TOPS is slightly better than the strimap mode, while the 2-look TOPS is worse due to the reduce azimuth resolution (and hence reduced number of looks). It can be shown that the performance ratio between two given modes in the estimation of the azimuth shift is given by

$$\rho = 10 \cdot \log_{10} \frac{\Delta f_1^2 \cdot B_{look,1}}{\Delta f_2^2 \cdot B_{look,2}}, \quad (1)$$

where Δf_i is the spectral separation and $B_{look,i}$ is the azimuth bandwidth of one look, which for all modes is equal to B but for stripmap, where it is equal to $B/3$ [11]. For the given examples, the gains w.r.t. the stripmap mode are 29.8 dB, 24.4 dB, 1.62dB and -1.38 dB, for BiDi, squinted SMs, $\pi-$shifted TOPS and 2-look TOPS, respectively. While BiDi offers the best performance, the two TOPS options have a larger coverage (100 km vs 30 km).

4. CONCLUSION

This paper has presented two experiments carried out with the TSX and TDX satellites over the Petermann glacier. Both exploit the angular diversity of two different modes. On the one

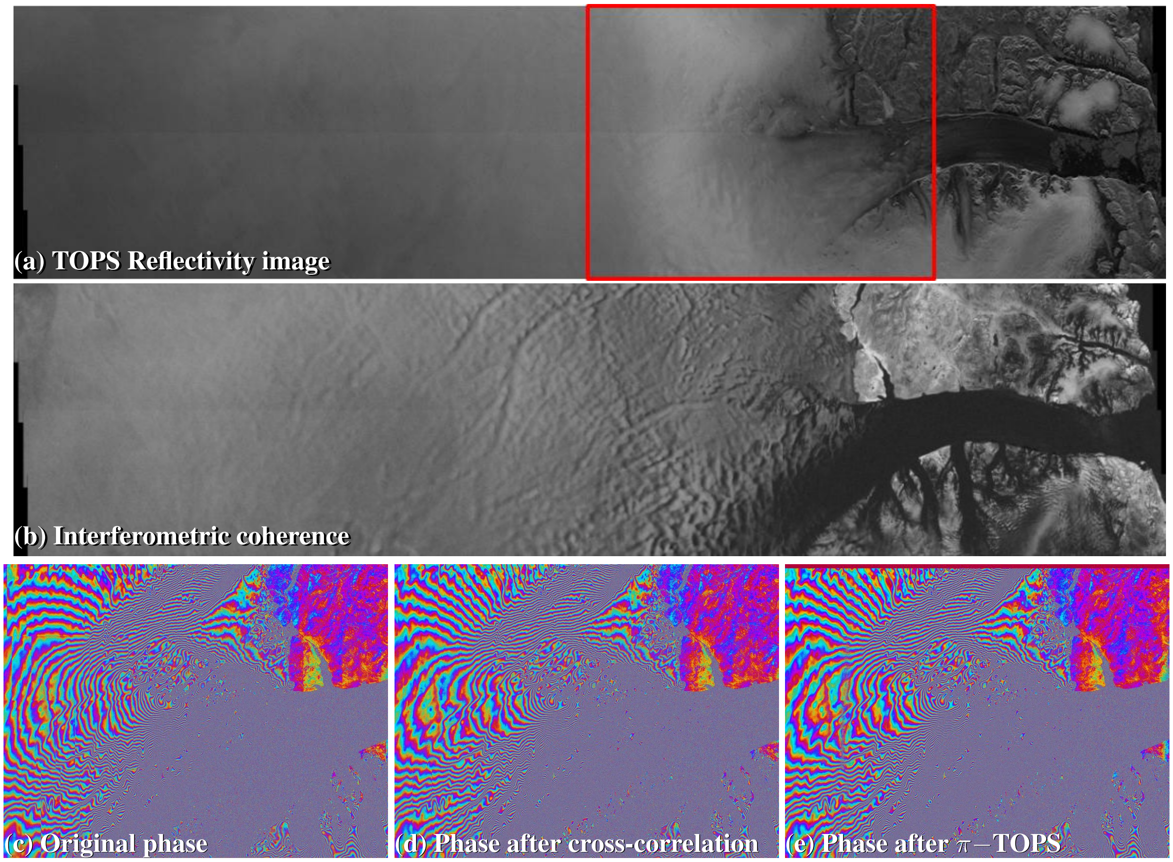

Fig. 4. $\pi-$shifted TOPS results. The red rectangle in (a) indicates the location of the DInSAR phases shown in (c)-(e). (c) is the original phase, where the phase jumps between bursts can be clearly observed; (d) shows an intermediate result after exploiting coherent cross-correlation, where the jumps are still visible in some areas; and (e) shows the final result after exploiting the $\pi-$shifted TOPS, where the jumps have disappeared, hence indicating an accurate estimation of the along-track motion.

hand, the bidirectional SAR mode in one single platform is exploited to directly obtain two different lines of sights. On the other hand, the $\pi-$shifted TOPS mode is exploited using both satellites during the TanDEM-X pursuit monostatic phase in order to preserve the azimuth resolution of 1-look TOPS and achieve at the same time a better angular diversity for the whole scene and not only at the burst overlap areas. First results with the TanDEM-X constellation have been presented, which demonstrate the potential of the BiDiSAR and the $\pi-$shifted (or 2-looks) TOPS to accurately estimate the azimuthal displacement within the scene.

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